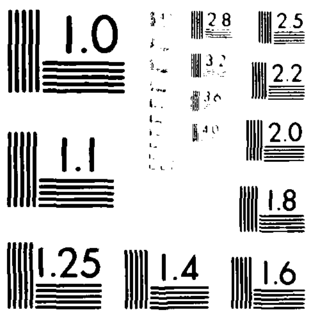
AD-A084 856   COAST GUARD WASHINGTON DC   F/G 8/5
AN APPLICATION OF INERTIAL SURVEYING FOR THE COAST GUARD.(U)
JAN 80 J J ANTHONY
UNCLASSIFIED USCG-D-1-80   NL

1 OF 1
AD
A084856

END
DATE
FILMED
7 80
DTIC



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

Report No. CG-D-1-80

AN APPLICATION OF INERTIAL SURVEYING FOR THE COAST GUARD

January 1980

FINAL REPORT

Prepared for

U.S. DEPARTMENT OF TRANSPORTATION
United States Coast Guard
Office of Research and Development
Washington, D.C. 20590

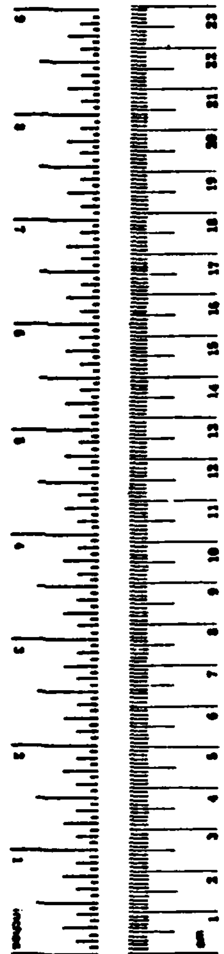
NOTICE

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

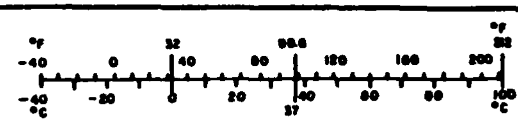
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



14

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
USCG-D-1-80	AD-A084 856	

4. Title and Subtitle	5. Report Date
AN APPLICATION OF INERTIAL SURVEYING FOR THE COAST GUARD	JAN[redacted]80
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
[redacted] John J. Anthony	
9. Performing Organization Name and Address	10. Work Unit No. (TRAIS)
U.S. Department of Transportation United States Coast Guard Office of Research and Development	702702.3
	11. Contract or Grant No.
12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered
Commandant (G-DST-1) U.S. Coast Guard Washington, D.C. 20593	Final Report
	14. Sponsoring Agency Code
	G-DST-1

6 11 10 9 16 12 141

15. Supplementary Notes

Inertial survey of Tampa Bay aids-to-navigation conducted jointly by National Geodetic Survey and the U.S. Coast Guard.

16. Abstract

Technological advances in both hardware and processor technology have spurred the adaptation of aircraft type inertial navigation systems to a sophisticated yet utterly practical tool for conducting surveys. The system, carried aboard a land vehicle or helicopter, is capable of rapidly performing position fixing over large areas in a minimum amount of time while providing survey grade output in real time. While inertial survey systems are being commercially exploited for land survey work, this paper describes a successful over the water application for surveying Coast Guard fixed aids to navigation. Included are descriptions of the equipment and its deployment along with recommendations for its use within the Coast Guard. Surveying experience with an inertial survey system suggests that it could be a cost effective tool for surveying many fixed aids over a large area.

17. Key Words	18. Distribution Statement
Surveying, Inertial Survey, Aids to Navigation, Positioning/Survey Systems, Geodetic Surveying, Offshore Survey.	Document is available to the public through the National Technical Information Service, Springfield, VA 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
UNCLASSIFIED	UNCLASSIFIED		

Form DOT F 1700.7 (8-72)

Reproduction of completed page authorized

086450 SW

ABSTRACT

Technological advances in both hardware and processor technology have spurred the adaptation of aircraft type inertial navigation systems to a sophisticated yet utterly practical tool for conducting surveys. The system, carried aboard a land vehicle or helicopter, is capable of rapidly performing position fixing over large areas in a minimum amount of time while providing survey grade output in real time. While inertial survey systems are being commercially exploited for land survey work, this paper describes a successful over the water application for surveying Coast Guard fixed aids to navigation. Included are descriptions of the equipment and its deployment along with recommendations for its use within the Coast Guard. Surveying experience with an inertial survey system suggests that it could be a cost effective tool for surveying many fixed aids over a large area.

TABLE OF CONTENTS

ACKNOWLEDGEMENTS

The author wishes to extend his most gracious thanks to the following individuals and organizations who either participated in or generously provided much needed assistance to this demonstration. Without their support, smooth and successful accomplishment of R&D goals would have been impossible.

U.S. Department of Commerce
National Oceanic and Atmospheric Administration
National Ocean Survey/National Geodetic Survey
Rockville, MD 20852

Span International, Inc.
Scottsdale, AZ

U.S. Coast Guard Air Station Clearwater
Clearwater, FL

U.S. Coast Guard Base St. Petersburg
St. Petersburg, FL

Pinellas County Engineers
Clearwater, FL

Hillsborough County Mapping and Survey Division
Tampa, FL

LCDR Lewis A. Lapine, NOAA

CWO4 Robert Couchman, USCG R&D Center

Mr. Harry Romine, NGS Geodetic Advisor for Florida

AN APPLICATION OF INERTIAL SURVEYING FOR THE COAST GUARD

I. Introduction

As marine traffic densities in our harbors and coastal waters increase both in numbers and tonnage, the Coast Guard has become more sensitive to the overall status and adequacy of its aids to navigation system. To provide the best service possible to the modern day mariner, materials and techniques which were once sufficient for smaller, slower moving traffic must now be improved. One particular area that has at times painfully come to the service's attention is the accuracy and precision to which visual aids to navigation are placed and have their positions reported. Evidence is available to suggest that improvements in the current methods of aid position reporting are necessary to both enhance information control of the system and improve the precision of navigation in general. As a result, there are now ongoing efforts by the operational Coast Guard to improve current positioning techniques and by research and development (R&D) to evaluate new technologies that show promise of assisting this endeavor.

Over 90% of Coast Guard floating aids are placed using resection techniques, that is, defining lines of position by measuring the horizontal angles between pairs of objects with known positions. Obviously, the accuracy of the known positions is critical to the resultant accuracy of the floating aids. Historically, buoy tender personnel have used objects whose positions appear on nautical charts and then determined the LOPs graphically with a three arm protractor. Modern methods employ analytic techniques that compute the value of the angles given only the geographic positions of the objects and observer. Such a scheme permits selection from many more objects that those charted, a necessary prerequisite to permit selection of LOPs with good crossing angles. Since a great many of the objects whose use is desirable are not certified to third order surveying standards (considered essential for obtaining good positions) in published horizontal control data, it becomes desirable to survey objects for aid positioning alone. In addition, the Coast Guard desires to determine the positions of as many of its fixed aids to navigation as possible to third order standards, both for the purposes of accurate reporting to the public and for similar use in placement of floating aids. Both of these tasks will require a tremendous amount of surveying.

The Coast Guard, however, lacks resident surveying expertise and must seek alternative means to conduct these surveys. While development of in-house talent is being considered, such a course of action will be very expensive, in both money and manpower, and would therefore be pursued only in the event other options could not provide a solution to the needs. The advantages of resident talent include quick response, good control over surveying operations and prompt reporting of the results. Other means to perform the surveying would be to contract commercial firms or utilize the services of the National Ocean Survey (NOS) whenever their schedule permits. Unfortunately, commercial surveying is relatively expensive and one always assumes a risk of less than satisfactory

results, especially when unfamiliar with the professional capability of the surveyor; Government surveyors may be utilized in lieu of commercial, but the survey may not be accomplished as quickly as desired. In short, it appears difficult to obtain the advantages of resident talent without some compromise.

Investigations by Coast Guard R&D have disclosed a new and exciting application of inertial navigation technology for surveying that has potential utility for Coast Guard requirements. Inertial navigation, as it is applied in aircraft equipment, is based upon frequent sampling of the output of horizontally mounted accelerometers to obtain the distance moved. Accelerometer platforms are stabilized with vertical seeking gyros so that distances are accumulated in the north-south and east-west directions only. Extension of this equipment to surveying requires more precise computation and more frequent updating to minimize error accumulation, but the principle is exactly the same. The resulting hardware, termed an inertial surveying system (ISS), can perform a survey task automatically, thereby minimizing the opportunity for human error to affect the results. The system is normally mounted in a vehicle (land based or helicopter) and transported to the locations to be surveyed. Using known endpoints, e.g., geodetic control stations, and appropriate procedures, any number of new stations may be surveyed in between. Third order accuracies or better appear achievable under most modes of operation. The speed at which a survey can take place is limited only by the speed of the host vehicle. Due to the advantages of such a system, including the tremendous distances and number of stations which may be covered while employing just a few operators, the ISS is being actively pursued by the community of surveyors, including NOS. Though these advantages are partially offset by the requirement for a competent survey party chief of considerable expertise, minimizing the traditional heavy reliance on numerous survey party members is a distinct advantage for a Coast Guard that lacks type of manpower. Technically, the system is a known quantity; its capabilities and limitations well documented. It has not, however, received any use in an over the water survey so the success of such an application was uncertain. Since any potential utility in the Coast Guard would require this type of operation, it became desirable to test deploy it operationally.

This concept of airborne inertial surveying was thus demonstrated in Tampa Bay, Florida, in determining the positions of several fixed range markers. Coast Guard R&D, in conjunction with the National Geodetic Survey (NGS) of NOS arranged and conducted the system's deployment, and prepared this report which includes an analysis of the prospective use of the system for Coast Guard needs.

II. Background

The idea of applying inertial navigation technology to surveying is not new. Preliminary attempts in the 1960's met with limited success due primarily to the inability of the computing equipment associated with the inertial navigation hardware to withstand shock and vibration during use (1). Precursor to the present day inertial survey systems was a Postioning and Azimuth Determining System (PADS) developed by Litton and the U. S. Army Engineer Topographic Laboratories between 1965 and 1972. This included the installation of a vertically mounted accelerometer in the basic inertial hardware, making elevation measurements possible. This first successful development provided position and elevation accuracies to within 20 and 10 meters, respectively. Additionally, its ability to be used during day or night, in any weather plus rapid transit over long distances made it immediately unique among all other positioning systems.

Subsequent modifications included a post mission smoothing program, installation of a more sensitive vertical accelerometer and additional modifications in the Kalman filters. Accuracies improved to better than five and two meters for position and elevation, respectively (1). This equipment then became the basis for the present Litton Auto-Surveyor.™

Since 1975, Canadian surveyors have increasingly turned to inertial systems to conduct their survey work. After gaining some experience in its deployment, they quickly realized its tremendous advantages for rapid long range surveying and opted to purchase a system of their own. Some excellent articles describing their operational and experimental use of the equipment appear in papers by Carriere, Beattie and Babbage (2,3,4).

Besides the U.S. Army, the ISS has now sparked interest among commercial concerns and the National Ocean Survey (NOS). The first major surveying task undertaken by NOS using the system was a 300 mile traverse along the coast of Louisiana, setting stations for later use in offshore hydrographic work. The ISS at this time appears to be capable of second-order horizonal control closures as specified in the FGCC "Classification Standards of Accuracy, and General Specifications of Geodetic Control Surveys". Appropriate procedures to follow to achieve this are currently under development for official dissemination.

Previous Coast Guard testing of the ISS was performed by the R&D Center in Casa Grande, Arizona, in January, 1979. At that time, the system was being considered as a means to conduct a survey of the Loran C grid in certain locations of the U. S., notably, the Chesapeake Bay. Long periods (10 - 15 min.) on station while hovering over water make a Loran C survey considerably different from a more "conventional" inertial survey where on station stops are as short as 30 seconds. Testing was confined to the determination of error accumulation over time and that resulting from significant deviations from a straight flight path. No attempt was made to deploy the equipment on an operational mission as subsequent analysis of the data would dictate how such a mission should be planned. Details of this data, in a report format, are available in reference (5).

Deploying an ISS for aid to navigation surveys or object position determination represents a more conventional use of the equipment. A helicopter based system used in the air mode (see Section V) is the only practical method for surveying objects since they are above ground or over water and may not be accessible by land vehicle. Indeed, for applications over large areas, the helicopter has been determined to be the most cost effective tool (2). The aids selected for survey in Tampa Bay reside within 150 sq. mi. (see figure 1) and the long stretches of water afforded an ideal environment in which to apply the air mode of surveying. A first check of the horizontal control in the area showed enough density of control that the whole concept of surveying in the area appeared quite feasible. On this basis then, the machinery to execute the survey was set into motion.

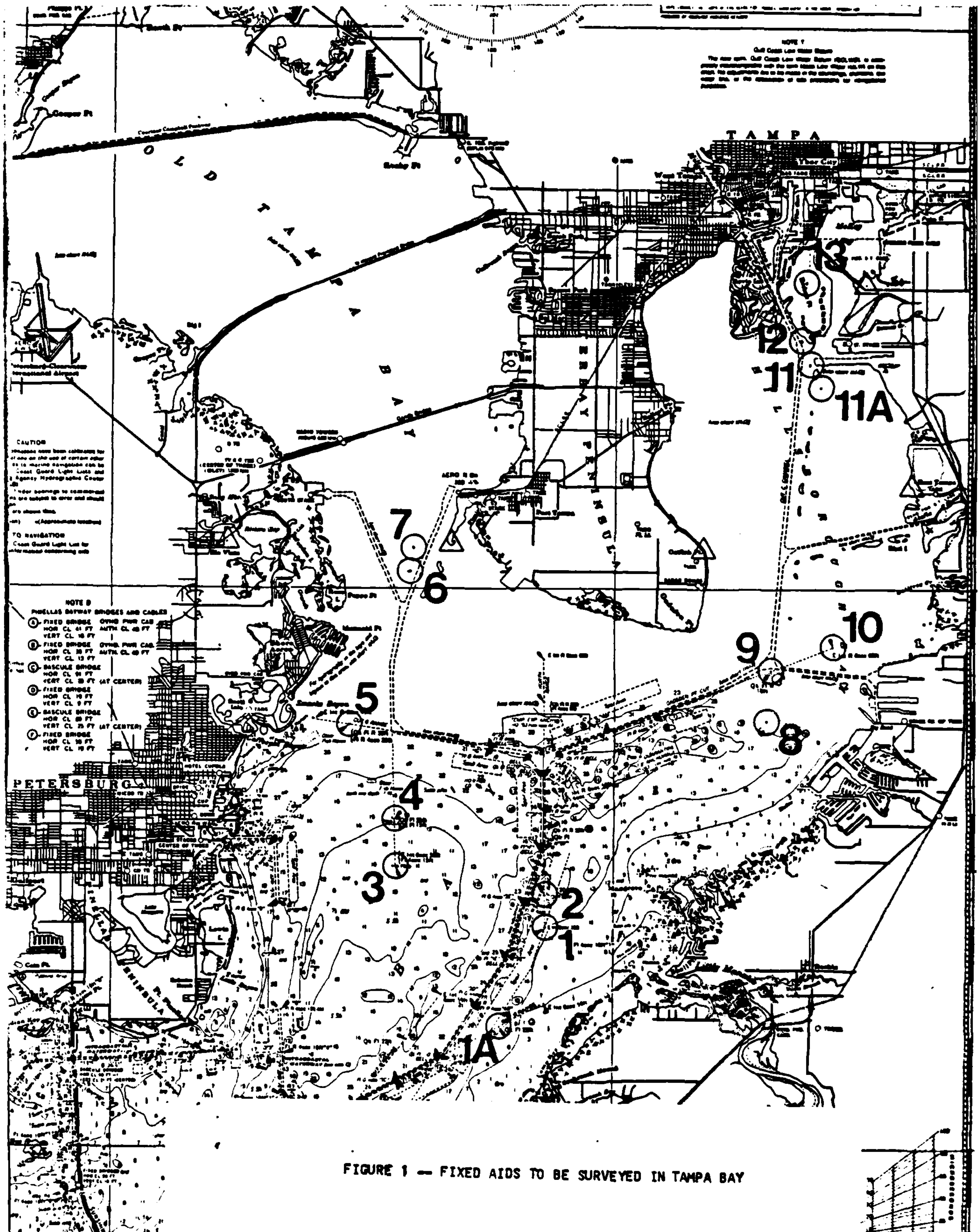


FIGURE 1 — FIXED AIDS TO BE SURVEYED IN TAMPA BAY

III. The Deployment in Tampa Bay

Any successful surveying project requires the advice and direction of a professional surveyor. In keeping with this precept, Span International, Inc., the only U. S. lessor of an inertial surveying system, requires in their contract for leasing the Spanmark™ ISS, "The User will provide a qualified surveyor to be in professional charge of the survey..." (Appendix A). Lacking this kind of talent within the Coast Guard, it was fortuitous that the National Geodetic Survey (NGS) was planning a mission of their own in the near time frame. Their contract with Span International, Inc.,* provided for 14 days of operation to conduct a 300 mile traverse along the Gulf coast of Louisiana. Following an evaluation of the survey jobs, it was plain there would be time available within the 14 days to perform the work in Tampa Bay. On this time permitting basis then, NGS included our work as part of their contract.

Having the expertise at NGS available to the Coast Guard for this deployment permitted the entire effort to take place more smoothly than would have been possible otherwise. The body of professional knowledge at NGS is immense, and was informally accessed at various times for publications, advice, direction and feedback on the Coast Guard planning of the mission.

A cursory examination of the most recent (1962) Geodetic Control Diagram (figure 2) revealed horizontal control stations with promising access by helicopter near the range markers. More up to date listings of the first, second, and third order control for the area with their associated descriptions were then obtained from NGS. Scrutinizing this information both eliminated some candidate sites which are now no longer in existence and added some new locations not pictured on the control diagrams. A list of candidate sites was then prepared for recovery.

Recovery of the horizontal control in the area surrounding Tampa Bay and reconnaissance to determine operational feasibility of landing a helicopter was performed by the Coast Guard. Additional support for this operation was received from Coast Guard Base St. Petersburg, which supplied a small boat with crew on two occasions; CG Air Station Clearwater, which provided fuel and parking for the NOAA-owned helicopter; Pinellas County Engineers, who provided maps and voluntarily flagged control stations for aerial observation and Hillsborough County Mapping and Survey Division, who assisted in the recovery of a control station that had poor accessibility. Pre-positioned offsets from a station, necessary at some locations to permit helicopter landing (see air mode of operation), were surveyed by the Coast Guard.

Following this preparation by the Coast Guard, NGS, who had recently acquired some expertise in the planning of these inertial surveys for their own work, helped to map out the legs to travel. This was done in

* Note: At this writing, Span International, Inc. is the only lessor in the U.S. that provides an ISS and associated services. Details of the contract appear in Appendix A.

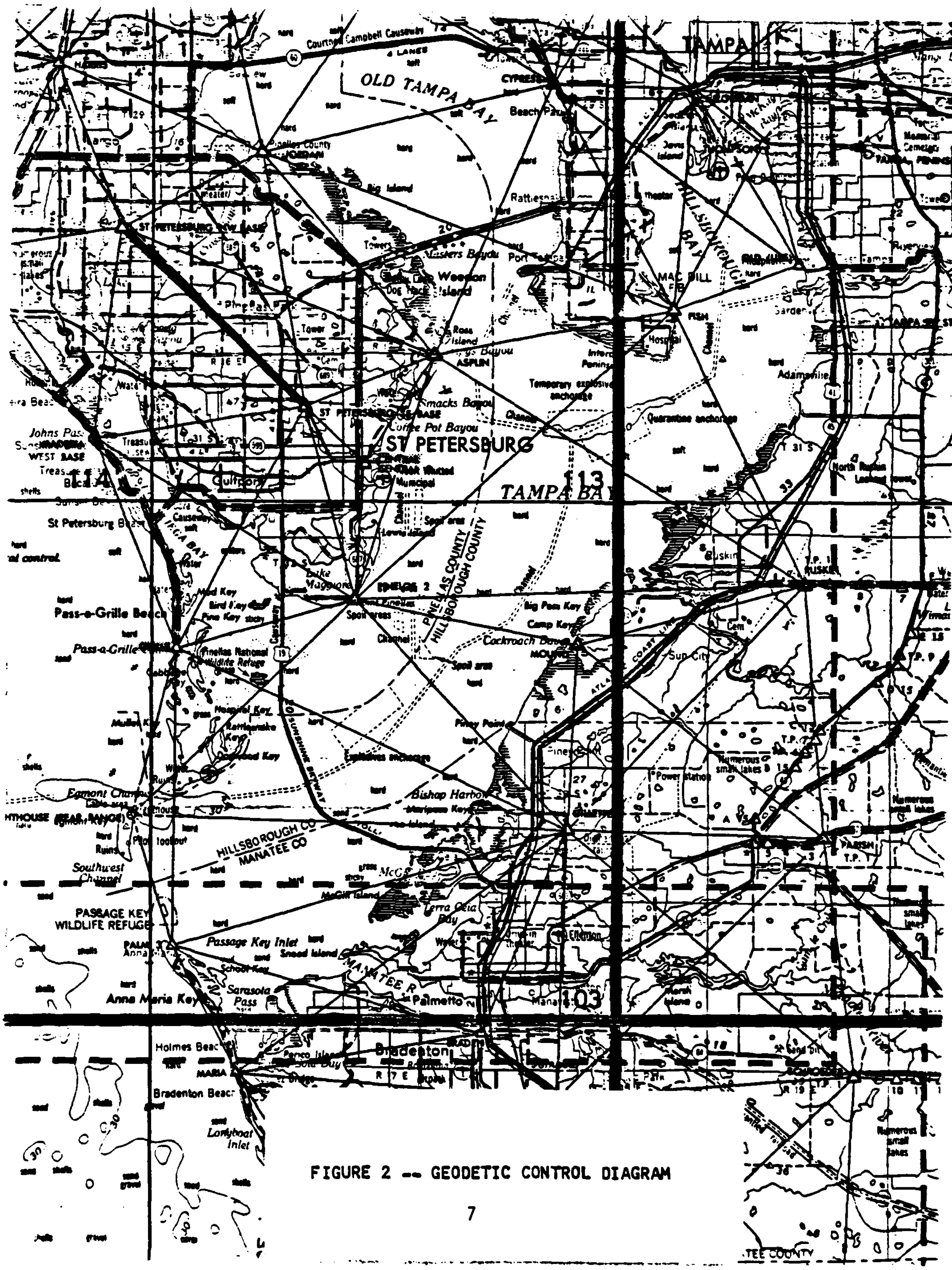


FIGURE 2 -- GEODETIC CONTROL DIAGRAM

accordance to the guidelines of experienced users (6, 7) and the contractor's own recommendations. These criteria are summarized in Appendix B. An initial plan included eight legs, some 230 miles of flying and three fuelings. Additional preparation on scene resulted in a more efficient mission consisting of only five survey legs and an additional calibration run. The mission as planned is shown in figure 3. Establishment of a new position on Picnic Island in the course of running route B provides the endpoint for route C.

The traverse legs were designed to be as straight as possible. As pointed out in the literature, keeping cross track deviations between endpoints less than 1/12 of the straight line distance will yield the most accurate results. In doing so, at NGS' recommendation, aid number 13 had to be deleted from the survey as there was no track close enough to cover it. It is now believed it too could have been surveyed, but there was risk the smoothed results for that track (D) may have slipped below third order standards. Each leg was to be flown in the forward and reverse direction to reduce the effect of systematic errors.

The ISS smoothing programs compute the precision of the determined position as it relates to the endpoints of the track, but there is no means to confidently express this in terms of how the position determined by the ISS compares to a position determined with conventional equipment and procedures. To permit some amount of comparison, an additional aid was added to track A, number 1A. Published horizontal control data already existed for this position; how close the ISS came to predicting its position would provide a good indication of overall survey quality. In addition, the R&D Center surveyed aid number 11A by intersection so that its position could similarly be compared.

Upon completion of their surveying operations in Louisiana, NGS flew the helicopter and ISS to Tampa. From there, NGS and the CG conducted a pre-survey aerial reconnaisance of the area, landing at all the update stations (endpoints), identifying ZUPT (zero velocity update) locations (see Section V), and hovering at the range marks to be surveyed. This preliminary flight is most important as it familiarizes the pilot and surveyor with the area, minimizing confusion at the time of the mission. Upon arrival of the personnel from Span International, Inc., the entire survey was carried out the following day.

All normal procedures for a typical ISS operation were followed. Alignment proceeded without incident in the morning, and the N-S, E-W calibration runs were performed. Execution of the survey continued along the planned routes A and B until six aids had been marked and a new geographic position on Picnic Island (the update station for route C) had been established. In the midst of running the next legs, the ISS computer detected an overtemperature condition and halted data collection, which necessitated a complete system realignment. Operations then continued along leg C to mark aids #1 and #2. Only legs D and E remained but while traversing leg D, the helicopter developed a mechanical difficulty in the tail rotor transmission that forced an emergency landing and precluded completion of the mission.

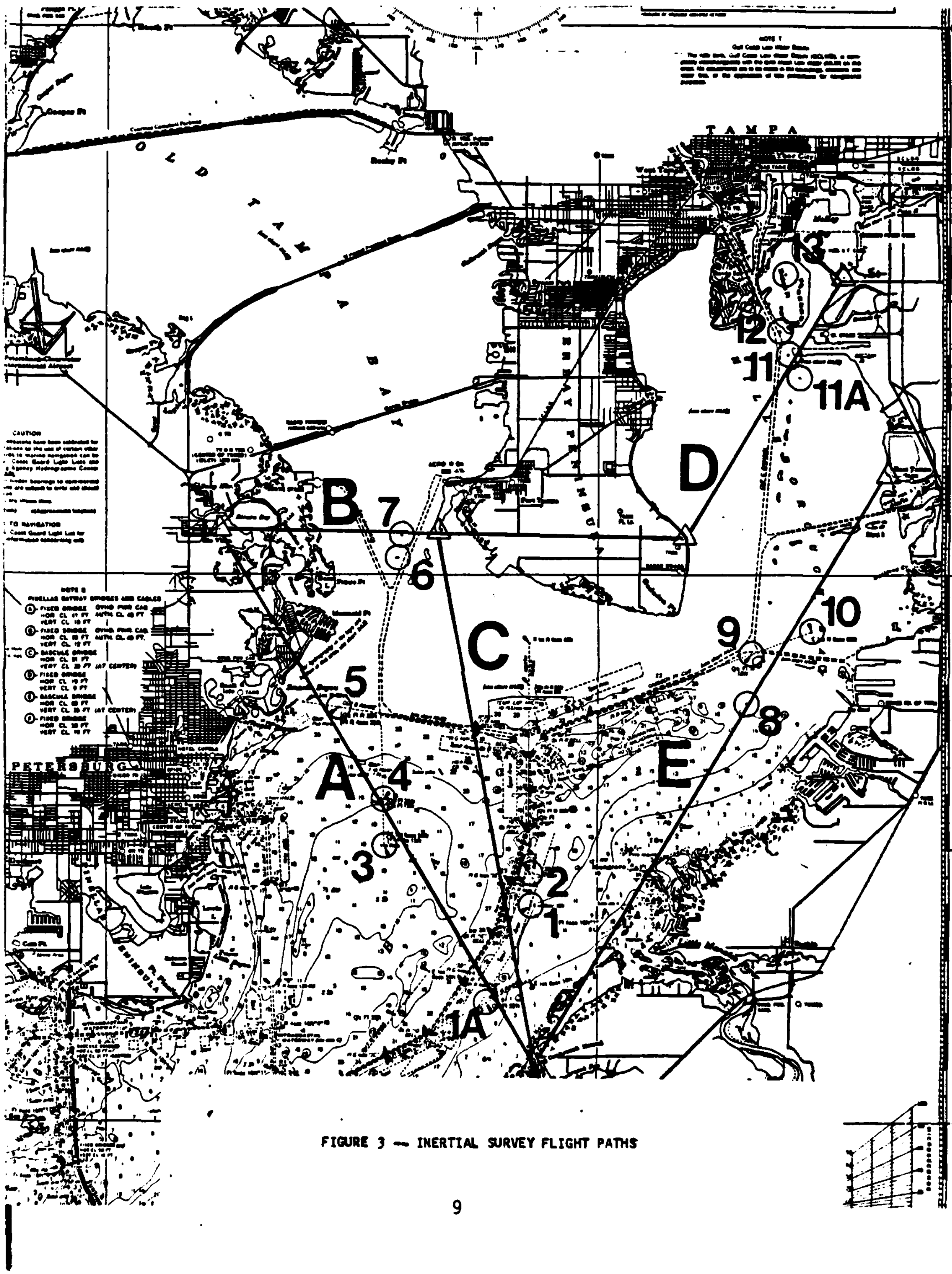


FIGURE 3 — INERTIAL SURVEY FLIGHT PATHS

It should be noted that while a failure of the ISS and a helicopter failure are both rare events, for each to occur in the same day on the same job is highly unlikely. This demonstration was planned to be conducted in a short time frame not to be too influenced by such events. Fortunately, a good portion of the survey was successfully completed before involuntary abortion of the mission.

Most of the post mission smoothing of the survey data could be completed on scene with Span's computer. The surveyed positions for the range markers appeared to meet the criteria for a third order class I survey (1:10,000) which is a good sign of consistent data. Following further analysis by Span, NGS received the final positions a week later. For reasons of safety, the helicopter could not hover directly over the exact center of each range light. Instead, a convenient corner of the aid was selected for positioning and it was that point which the ISS surveyed. Following the helicopter work, each aid was occupied to measure the vector offset from the corner to the light. Forward geodetic computation was then performed on the smoothed positions from Span to correct for the offset. Following final adjustment to the North American Datum of 1927, these positions may be incorporated into NGS published horizontal control data. For information purposes only, Appendix C lists the preliminary, and as yet unspecified and unadjusted, positions.

IV. Theory of Inertial Systems

The heart of an inertial navigation system is a platform that is stable in some reference frame be it space, surface of the earth or some other. The platform is stable due to the action of at least two orthogonally positioned gyroscopes, stabilizing four degrees of freedom (one is redundant as the platform has only three). In a system oriented about the surface of the earth, one gyro is usually vertical seeking, which provides for local platform leveling, while the other is north seeking and provides horizontal stability. In space oriented systems, one gyro remains aligned with the axis of the celestial sphere (i.e., pointed toward Polaris). As the earth spins, the vertical seeking gyro in earth oriented systems, while stable in space, will deviate with respect to the reference frame. To maintain proper alignment, the gyro is continuously torqued to induce precession in the correct direction with the required torque being computed from the earth rate. Torquing of the gyro in a space oriented system is of course not required.

Three accelerometers, all mutually orthogonal, are mounted on the platform. These are nothing more than precision pendulums that can detect accelerations as small as one micro-g. Periodic sampling of the accelerometer output is continuously integrated twice to yield cumulative distance in the direction of the accelerometer's axis. After conversion to distances in latitude and longitude, these position coordinates of the unit are displayed on a display unit. Updating of the display takes place as often as accelerometer interrogations.

The differences in an inertial survey system and a navigation system are mostly improvements in precision, obtained by using higher quality gyros, higher resolution accelerometers and smaller time intervals between accelerometer sampling combined with predictive computer routines. While this will radically improve the raw measurement being taken in a survey, only with post-mission smoothing and analysis can the equipment begin to produce results that achieve the standards of precision required in geodetic control work (i.e., better than 1:10,000).

V. Technical Description of the ISS Equipment

The best descriptions of ISS equipment, including the preferred methods for deployment, appear in a collection of papers given at the 1st International Symposium on Inertial Technology for Surveying and Geodesy in Ottawa, Canada, during 12-14 October 1977 (8). The state of the art has advanced considerably since then with the rapidly growing acceptance of the equipment and its adoption by numerous surveying concerns. This has given use to a great many improvements, mostly in system software, that considerably enhance the basic inertial unit. Some of these are reported in the above reference; others will be the subject of future symposiums. This section summarizes the descriptions contained in references 7 and 9 of the equipment used in this operation. It then launches into a discussion of error sources of the equipment and its use, error accumulation and the rectification of the errors.

A. Auto-Surveyor™ and Spanmark™ Inertial Survey Systems

The most widely used ISS at the present time is the Litton Auto-Surveyor™. This is actually a twice modified version of the LN-15 inertial navigation system (INS), vertical seeking two dimensional aircraft instrument. The two modifications consist of:

(1) conversion to three dimensions with the addition of a highly accurate vertically mounted accelerometer, and

(2) inclusion in the computer of more sophisticated software optimal estimation techniques.

The resulting system is thus capable of performing both horizontal and vertical position determinations with an accuracy compatible with geodetic standards.

Components making up the complete system are an Inertial Measuring Unit (IMU), Data Processing Unit (DPU), Power Supply Unit (PSU), Control and Display Unit (CDU), and a digital data storage device. This complete package can be installed in a ground vehicle or medium sized helicopter capable of supplying 60 amp, 24 VDC electrical power.

The IMU contains all the inertial hardware, mounted on gimbals within the case. Electronic assemblies external to the gimbals control internal temperature, deliver precise power and process the signals received from the accelerometers. Resolvers on the three axes of the gimbal set send information on azimuth, roll and pitch of the instruments with respect to the IMU case. Drift rate of the gyros is less than 0.001°/hr, the horizontal accelerometers have bias errors less than 5 micro-g's and the vertical accelerometer has a bias of less than 1 micro-g.

All computations are performed in the DPU, a digital computer with 12K of memory. This computer performs all analog to digital conversions and provides real time survey information to the operator. Software

routines include testing for reasonableness of data, control of system errors, inertial alignment and calibration and inertial data smoothing at the close of a traverse.

The operator interfaces with the system through the CDU. This displays current position and system status. Position update coordinates, inertial alignment, and surveyed marks are all input through the CDU. Normally mounted near the operator, it also informs the user when he is required to perform a specific operation, such as a ZUPT.

The PSU is essentially a power distribution box that receives vehicle power and provides 24 VDC to the batteries and all other components. Precision voltages, when required, are generated at the unit using the power.

A cassette tape records all the survey data marked during a traverse, the inputed update points and the smoothed date computed in the DPU at the time of an update. This tape may be used in post mission smoothing programs that perform the final position determination.

Span International, Inc. has reconfigured and modified the basic Auto-Surveyor™ described above to further enhance its use in a practical survey environment. Software changes now permit more stations (up to 140) to be surveyed along a track, selectable time intervals between ZUPTs, selectable error tolerances during a ZUPT, and more versatility in the placement of fixed offsets from the IMU. Perhaps the modification with the greatest impact is the installation of a laser ranging instrument on the IMU. With this feature it is possible to determine the offset to any nearby point by aiming the instrument at a reflector mounted at the point. Thus the survey vehicle need not position itself or the inertial system directly on the point whenever it has poor accessibility. The range from the laser ranging equipment, universally referred to as an electronic distance measuring distance measuring instrument (EDMI), and the azimuth from the IMU are manually input to the DPU where it is processed to mathematically move the IMU to the marked position.

The Spanmark™ may be used in one of two modes, ground or air. Though the inertial components perform the same in either instance, the software routines are considerably different. In the ground mode, all alignment, position updates, position marks and ZUPTs are performed on the ground, either in a land vehicle or a landed helicopter. The laser geodimeter may be used at various distances to 100 meters (subject to the vibrational stability of the vehicle) whenever the vehicle cannot be positioned at the station. The allowable movement during a mark, update or ZUPT will be very small and the software "window" for movement can be set at less than 0.005 feet.

When positions are to be surveyed in locations that do not permit a helicopter landing, the air mode is used. Normally, a hover sight is installed on the helicopter directly beneath the pilot so he may orient the aircraft in a hover directly above the position being marked where a

succession of three readings are taken before the traverse is continued. ZUPTs may also be performed in a hover, but the software "windows" allow 0.01 feet or more of movement since the aircraft cannot be as stationary as when landed. Because obtaining positions in the air by sighting presumes no offset, air mode software routines in the present Spanmark™ do not permit use of an EDMI. Furthermore, inclusion of this capability would require compromise of other features due to the limited storage capacity in the on line computer. Thus, when positions are surveyed on the ground while in the air mode, the system reference point must be placed directly over the position.

Since many survey points and control stations are not directly accessible by helicopter, new positions in clearer areas must be offset from the desired point prior to the helicopter flight. If the location is an update point, prior computation of the position's coordinates is necessary so they may be input to the CDU at the time of the survey. Though incorporating EDMI routines in the air mode software is not an impossible task, the number of instances when it would be required is small and therefore Span sees no economic incentive to develop it at the present.

B. Error Sources

Three types of errors exist in an ISS--equipment biases, systematic errors due to operation and noise.

The first two types are normally treated as systematic errors and are corrected in combination. Contributing to these errors are:

1. initial velocity error, may typically be 0.001 fps
2. gyro (platform) drift rate, 0.001°/hr
3. accelerometer measurement error
   (a) bias error
   (b) scale factor
   (c) misalignment of accelerometer axis
4. environmental effects
   (a) temperature
   (b) magnetic anomalies
   (c) vibration disturbances

Error growth for each of these sources is linear and can be corrected with suitable linear models. But since their effect is twice integrated for distance measurements, error growth is nonlinear and if allowed to

persist along a traverse, will soon take on characteristics resembling an exponential as shown in figure 4a. In the first three to four minutes however, the growth is linear, predictable and capable of correction by the algorithms describing the linear model. Thus the system is periodically stopped every three to four minutes for what is a zero velocity update (ZUPT). These stops require anywhere from 20 to 60 seconds during which the system is informed it is stationary. The Kalman filter then proceeds to estimate the error accumulated over the time interval since the last ZUPT, corrects for it and stores the system's position. Releveling and realignment of the inertial platform takes place during the stop so that the system essentially makes a fresh start when movement recommences. Starting the traverse from a known position A in figure 4b, ZUPTs are continually performed along the route until the system reaches another known geographic position, 2, at which time it performs a position update.

Despite the corrections for error that have taken place along the traverse, the actual position will probably differ from the predicted position as shown in figure 4c. This is a result of very slight inaccuracies of the linear model and differences between the predicted components of gravity, magnetism, temperature and earth rate and their actual values. Given the actual position, the computer distributes this difference along the traverse similar to figure 4d. Now the same traverse is executed in the reverse direction, including ZUPT until the system's position is updated once again at point A. The distribution of error will now have a similar shape to that resulting from the forward traverse only on the opposite side (figure 4e). Post mission processing of this data will average the error distributions and compute the vehicle's track, which should be identical to the actual. Given symmetrical distributions, it will be.

No computation can be performed to indicate just how symmetrical the distributions are. Good symmetry results from good survey procedures including well placed ZUPT stations, accurate update positions and equal times to traverse forward and reverse. Position error, after correction, of the surveyed stations along the traverse that remains uncorrelated with error of other positions, is the result of noise. While this cannot be rectified through any software filtering, its impact can be reduced by knowing what causes it and how it grows. The reader is referred to a good discussion of the subject by Huddle in reference 9. Suffice it to say here that the small residual errors due to noise appear to grow as the square root of the number of stops along a traverse. Much of this can then generally be corrected in post mission smoothing.

C. Prevention of Uncompensated Error

In light of the high accuracies achievable with an ISS and the employment of sophisticated error minimization schemes, far more critical to the success of a survey is close adherence to proper procedures on the part of the user. The following four major areas of carelessness or poor

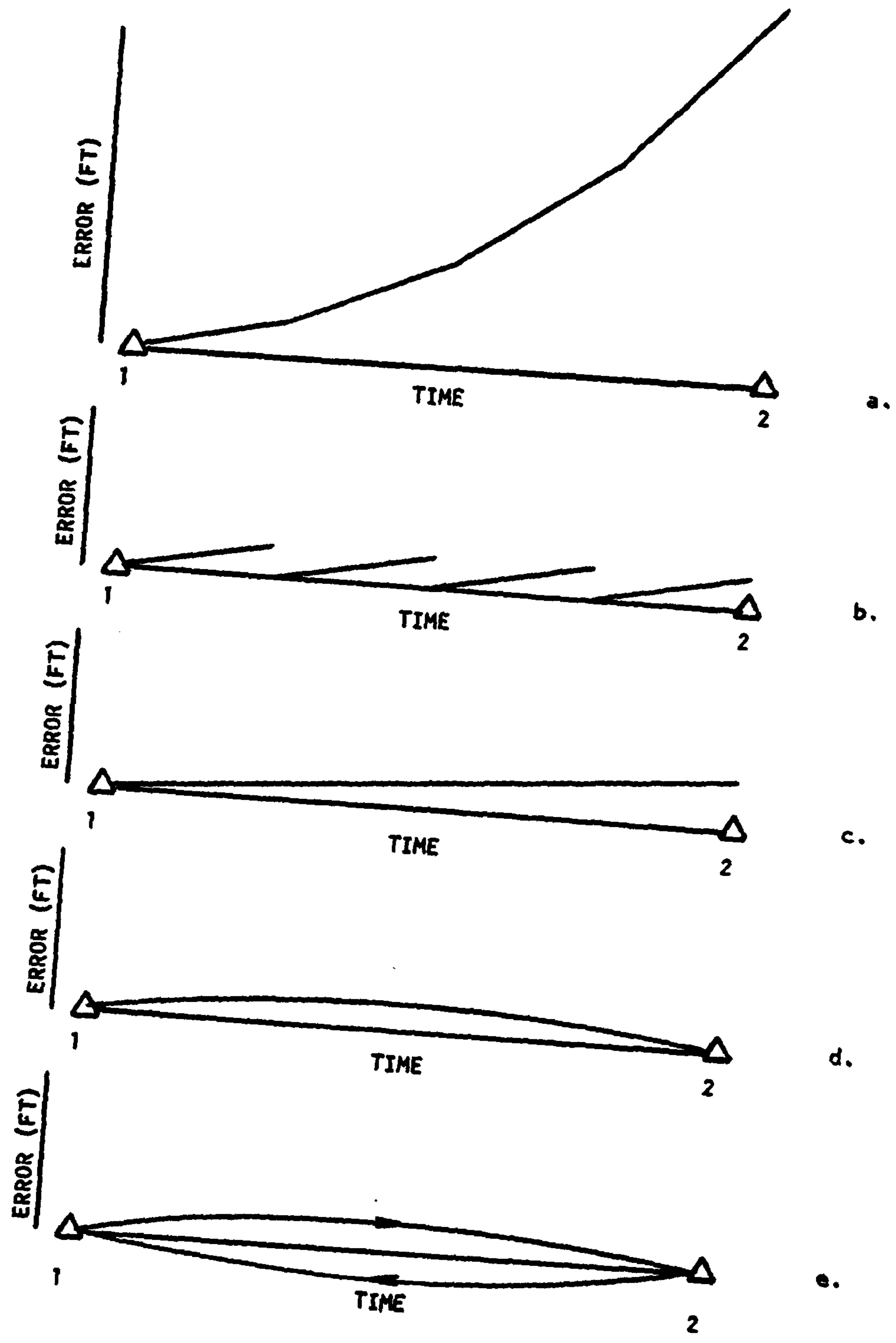


FIGURE 4 -- RAW AND SMOOTHED ERROR DISTRIBUTIONS ALONG A TRAVERSE

planning will result in something less than optimum positions. Wickam (7) provides a very complete listing of these and other less critical considerations.

(1) Excessive deviation from a straight line track - Though the Kalman filter and frequent accelerometer sampling intervals (every 16 milliseconds) provide superior position prediction, the gyros and accelerometers are sensitive to changes in the temperature and magnetic gradients. Over a straight line traverse these effects are linear enough to not be a significant contributor to error. Cross track deviations of more than one-third of the along track distance may subject the equipment to different gradients that affect the precision performance of the internal components. As reported by Hadfield (11), future generations of inertial surveying systems using more sensitive accelerometers and gyros combined with extensive shielding may eliminate the need to adhere to a straight line. In the meantime, any surveys performed with the Spanmark should be planned with the goal of keeping cross track deviations less than 1/12 of the along track distance.

(2) Poor geodetic control - Since any survey will only be as good as its control, only those stations with verified positions should be utilized. Ideally, the order of the station should be one better than the order of the survey. Equally important is to position the survey vehicle precisely on the center of the station. Since control stations are used for position update, error arising from their use propagates throughout the entire traverse.

(3) Excessively long intervals between ZUPTs - After 3 to 5 minutes, position error accumulation becomes nonlinear and cannot be completely removed with the linear models. Thus a small uncorrected position will remain in the system after a ZUPT that was performed past the time limit. The effect on the survey is equivalent to using an update control station with poorly reported position.

(4) Improper execution of ZUPTs - Since the purpose of the ZUPT is to place the system in a stable environment, any movement (velocity) that occurs during a ZUPT will permit the system to realign to a moving reference frame. Since it was told the frame was stationary, the small velocity error will remain uncompensated in the system until the next ZUPT.

VI. Analysis of the Utility of the ISS for the Coast Guard

The distinct advantage that the ISS has over more conventional techniques is the large amount of surveying that can be accomplished in a short period of time. In the case of the survey in Tampa Bay, this amounted to four hours of flying time plus an hour of aerial reconnaissance. In that time, the positions of eight aids and one location on shore were determined. Depending on the efficiency of the flying units and the density of the points to be surveyed, surveying 20 aids in a day is a good estimate. Using conventional methods on a similar number would require from one to three weeks. The benefit of time savings with an ISS cannot be disputed.

The advantages of time and large coverage area are balanced by high cost and extensive pre-mission planning. Since the surveying takes place so fast, all supporting functions must execute like clockwork. This demands that the person in charge have complete knowledge of the area, have made a pre-survey reconnaissance of the routes and positions, and tended to all the many logistical considerations such as timely refueling of the helicopter. Extensive planning is always a prerequisite for any successful survey, but never is it more critical than with an inertial survey. Neglect of even minor details can ground the system for hours, incurring large expenses in the process. Carriere (2) states, "The cost per (surveyed) station.... traversed will be inversely proportional to the time taken to properly prepare a project," which is in consonance with the experience of other users. The contractor will provide all the technical assistance that may be needed, but generally will not assist in the planning. It is highly recommended then that the surveyor in charge of the operation familiarize himself with available literature or have had previous experience with inertial surveying. A short guide to some important field preparation considerations is provided in Appendix D.

The Coast Guard must weigh its requirements for accurate aid surveying against the cost, time, and benefits achieved in such surveys. A short cost analysis is presented here to place the ISS in perspective with more conventional methods. Economic considerations alone will generally determine how a survey will be conducted. The reader, however, must appreciate the fact that each survey has its own peculiarities, and such items as availability of control, access by land vehicle for recovery, the extent of the area to be surveyed, and weather/environment considerations may favor one method over another, regardless of the cost. Additional recommendations are included in section VIII.

<u>ISS</u> - Initial costs to lease an ISS are high as they must pay for all transportation, installation, initial testing, spare parts, and other overhead items. Span International, Inc. charges $12,000 for its mobilization fee (see Appendix A). Daily operating costs are $3325 for a seven hour period. Associated miscellaneous costs include per diem expenses for Span employees and any necessary ground support equipment.

All helicopter costs must be borne by the user of the equipment. A four passenger helicopter is considered ideal for equipment and passenger space while providing good maneuverability. Desirable features of a

helicopter include good downward visibility, small size, 300-400 jile range, floats for over water operations and good hovering characteristics. The ISS package has operated successfully in the Hughes 500 C, D, Bell 206 B, L, Allouette Llama and Fairchild 1100, so these models are highly recommended. The NOAA helicopter used in the Tampa Bay survey was a Bell Model 204 E. Coast Guard helicopters at present are not very adaptable to an inertial surveying job because of the lack of downward visibility, their larger size and the three point landing gear, which permits more vibration than simple floats or skids. Furthermore, regular operational commitments may preclude exclusive assignment of an aircraft to the surveying mission when it is required. For these reasons, commercial helicopter rentals will be another necessary cost in an inertial survey. Typical rental fees that include pilot and fuel currently average $300 per hour of collective time; the helicopter will be flying approximately 60% of the time.

Table I itemizes these expected daily costs of an inertial survey. To obtain the average daily cost of an entire survey, add to this the average mobilization fee per day. Note that the figures include the cost of the planning performed by the chief of the surveying project. Good use of in house manpower can be made during the planning stages which will cut the cost considerably. Planning for the one day Tampa Bay survey was conducted by four persons with a combined work load of one man month. Estimate an additional man week for every additional day of surveying. Depending on the extent to which in house talent is used and the characteristics of the area being surveyed, planning costs may average $500-$1000 per survey day.

<u>Conventional</u> - A conventional survey of aids to navigation is labor rather than equipment intensive. A commercial surveying firm bidding on an entire job would include recovering the control, targeting, performing the survey, and reducing the data in its estimate. Depending on the size of the survey, two to six men might be employed. As shown in Table II, one week of surveying costs approximately $5000 in an area with adequate control and good accessibility. Poor weather and visibility will hamper outside operations about 20% of the time (depending on the area) which may inflate the weekly figure to $6000.

<u>Comparison</u> - Comparison between conventional and inertial methods can be made on the basis of number of aids or on cost per aid. Any performance may be assumed but based on the Tampa Bay survey, the ISS can reasonably be expected to determine 20 positions per day of operation. Based on the experience of other surveyors (2, 4), a conventional survey will take up to ten times longer. Using these assumptions and the cost figures, figure 5 shows the direct comparison between the two methods. At 100 aids, the ISS becomes economically more attractive.

Alternatively, the cost of surveying each aid can be evaluated against various deployments of the ISS. In figure 6, the unit cost of surveying 50 aids is shown against the time of system rental. This may be compared to the unit cost of a conventional survey. For example, when the conventional unit cost is $600 per aid, the ISS is economically advantageous if the mission requires no more than two days rental.

Item	Estimated Cost ($/day)
ISS Daily Use Fee	$3325
Helicopter Rental (inch pilot) 7 hrs @ $300/hr, 60% use $2100 X 0.60 =	1260
Chief surveyor	100
Per diem expenses	350
Miscellaneous expenses Ground support Transportation	40
Pre-mission planning (est)	750
Post-survey computation and adjustment	1000
Documentation, publication, etc.	500
Total daily survey costs	$7475

Table I - Average Daily Cost of an Inertial Survey

Item	Estimated Cost ($/week)
Surveying Party - 3 man	$1500
Per diem expenses	1000
Equipment	500
Transportation and miscellaneous	500
Pre-survey recovery	500
Post-survey computation and adjustment	500
Documentation, publication, etc.	500
Total estimated weekly cost	$5000

Table II - Estimated Weekly Costs of a 3-Man Surveying Party

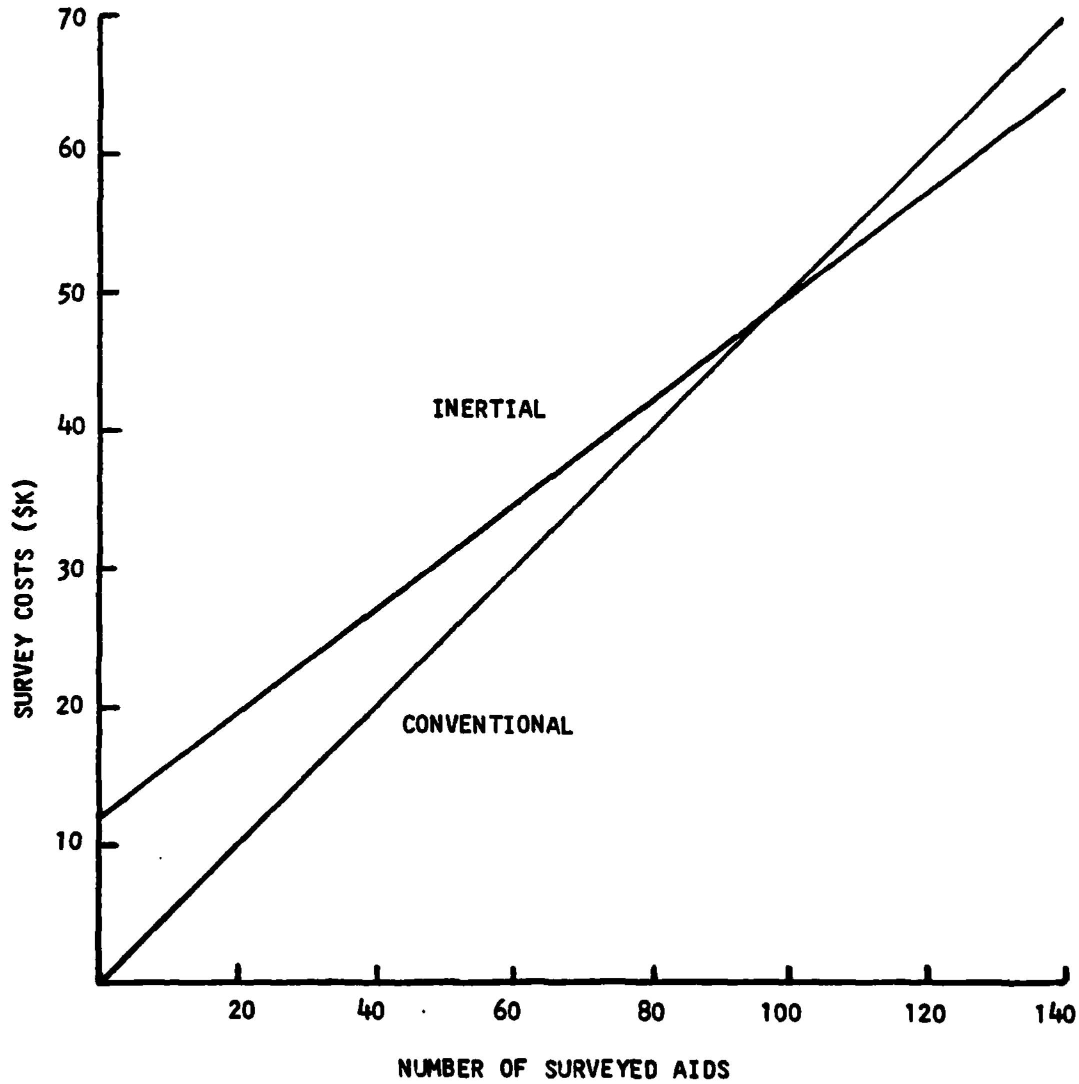


FIGURE 5 -- COST OF INERTIAL AND CONVENTIONAL SURVEYS AS A FUNCTION OF NUMBER OF AIDS

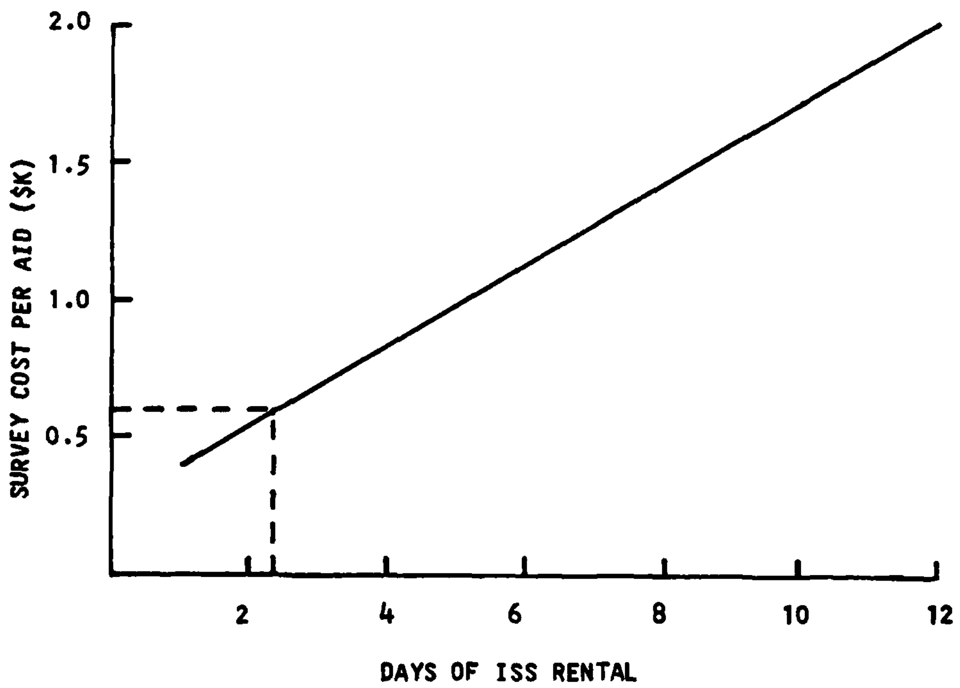


FIGURE 6 -- UNIT COST OF 50 SURVEYED AIDS VS. DAYS OF ISS RENTAL

VII. Conclusions

As a result of Coast Guard research to date and the operational deployment in Tampa Bay, the following conclusions can be drawn about inertial surveying.

1. The capability to use an airborne inertial survey system to perform an over-the-water survey of fixed aids to navigation was successfully demonstrated in Tampa Bay.

2. Inertial surveying is extremely rapid compared to conventional surveying techniques. Usable (although not yet publishable) surveyed positions are made available on scene or within 24 hours.

3. Though no official NGS-approved procedures exist, at this writing, the results of an inertial survey appear to be at least as good as third order. Surveys must be executed in accordance with current inertial surveying practice. This will usually provide sufficient precision for any Coast Guard fixed aid to navigation.

4. Because an ISS is an expensive and sophisticated apparatus and surveys must be conducted in a helicopter, the total cost of a given survey is high, usually exceeding $20,000.

5. Inertial surveying technology may be successfully applied to most Coast Guard surveying tasks whenever cost-benefit analyses are favorable. However, use of the system is not justifiable for a survey of a small number of aids.

6. Inertial surveys are fast and efficient for regions containing large numbers of aids. It would be an effective means for performing one time surveys of fixed aids to navigation in four or five adjacent harbors.

VIII. Recommendations

1. The Coast Guard, in light of its interests in more accurate aid positioning, should become familiar with all the various methods of surveying available to perform the tasks. This does not imply development of in house expertise in surveying but rather, a knowledge sufficient to intelligently contract for reliable, accurate and cost-effective surveying services.

2. Deployment of an ISS should not be attempted for surveys of a small number ($\sim$20) of aids. The cost and planning time cannot be justified for the benefits received in reduced survey time.

3. Inertial surveying should be considered another option which the Coast Guard may evaluate for its needs. It is potentially a very cost effective system to use for long range surveys with limited conventional access to control stations.

4. Coast Guard districts reviewing the status of survey control of their fixed aids may find a large number are not verified to third order. Should a large scale survey of these aids be considered, the ISS should be evaluated along with other methods to accomplish the task.

References

1. Todd, M., "The Development of the Inertial Rapid Geodetic Survey System at USAETL." Reference 8.

2. Carriere, R. J., Kouba, J. and Penney, R. C., "Experience with the Inertial Survey System at Geodetic Survey of Canada." Reference 8.

3. Beattie, J. C. and Welter, J. F., "Alberta Energy & Natural Resources Whitecourt Forest Management Area Control Survey Project 1977." Reference 8.

4. Babbage, G., "Operations of the Inertial Survey System: The Manager's View." Reference 8.

5. Couchman, R., "Investigation and Evaluation of Inertial Survey Systems for Harbor and Harbor Entrance Surveys of Loran-C Time Difference Coordinates," U.S. Coast Guard R&D Center Report.

6. Harris, H. C., "DMA Operations with an Inertial Positioning System (IPS)." Reference 8.

7. Wickham, J. H., "Inertial Surveying Technology in Private Practice." Reference 8.

8. First International Symposium on Inertial Technology for surveying and Geodesy, Ottawa, Canada, 12-14 October 1977.

9. Ellms, S., "A Description of the Auto-Surveyor System and Its Sub-System Accuracies." Reference 8.

10. Huddle, J. R., "The Theoretical Principles for Design of the Inertial Surveyor for Position and Gravity Determinations." Reference 8.

11. Hadfield, M. J., "Critical Inertial System Characteristics for Land Surveying." Reference 8.

SPAN INTERNATIONAL, INC.
SPANMARK™ INERTIAL SURVEY SYSTEM

DOMESTIC
USE AND SERVICE AGREEMENT

AGREEMENT NO. ______

INVOICE TO:	**AIRPORT OF DELIVERY:**
User	Airport Name
Street Address	City and State
City and State — Zip Code	Agent, Consignee, or User
( ) Telephone Number	**VEHICLE:** Land Vehicle ☐ Helicopter ☐

REQUESTED SYSTEM DELIVERY DATE: ________________

SPAN International, Inc. (hereinafter called "SPAN"), upon acceptance of this Agreement and receipt of the Mobilization Fee from the User, agrees to provide a SPANMARK™ System (hereinafter called "System"), together with maintenance, operator and all other services provided for herein under the terms and conditions hereinafter stated.

The BASE TERM shall be ______ days commencing on the date the System has arrived at the Airport of Delivery shown above.

User shall pay to SPAN a *Basic Charge for the BASE TERM as follows:*

Use Fee (Base Term days @ $3,225 per day) .... $ ________

Mobilization Fee .... $ 12,000.00

TOTAL BASIC CHARGE .... $ ________

The Basic Charge entitles the User up to a maximum number of Use Time hours (as hereinafter defined) equal to the number of Base Term days multiplied by seven (7):

Maximum Use Time hours = ______

If the System is used in excess of the Maximum Use Time hours stated above during the Base Term, the User shall be invoiced and pay to SPAN Three Hundred Seventy-five Dollars ($375) for each hour, or fraction thereof, in excess of the Maximum Use Time hours. Unused portions of the Maximum *Use Time hours stated above shall not be carried over beyond the Base Term.*

The Basic Charge is payable to SPAN according to the following schedule:

$ 12,000.00 Mobilization Fee paid upon *SPAN'S confirmation of a delivery date.*

$ ________ (50% of Use Fee) due on or before commencement of Base Term.

$ ________ (40% of Use Fee) due at the end of the Base Term. If the Base Term is longer than thirty (30) days, it shall be paid in pro-rated 30-day installments with the balance due at the end of the Base Term.

$ ________ (10% *of Use Fee) due upon submission of the final data from the System to the User.*

IF USER ELECTS TO PAY THE ENTIRE BASIC CHARGE PRIOR TO THE COMMENCEMENT OF THE BASE TERM, USER SHALL BE GRANTED A FIVE PERCENT (5%) DISCOUNT FROM THE TOTAL BASIC CHARGE.

At or prior to the completion of the Base Term, the System shall be returned by User to SPAN at the Airport of Delivery or such other location acceptable to SPAN. If the User requests the use of the System beyond the Base Term, subject to SPAN'S having a System available, the User shall pay to SPAN Four Thousand Five Hundred Dollars ($4,500) per day for such use plus Three Hundred Seventy-five Dollars ($375) per hour, or fraction thereof, in excess of seven (7) hours Use Time per day.

The Basic Charge and all other charges shall be paid by User to SPAN in U.S. Dollars at Scottsdale, Arizona, or at such other place as may be designated by SPAN. Additional use charges or other charges provided for herein will be invoiced separately and shall be paid by User within ten (10) days from date of invoice.

To the Basic Charge stated above, there shall be added amounts equal to any use or lease taxes, however designated, levied or based on such charges or on this Agreement or on the System or its use, including state and local privilege or excise taxes based on gross revenue, and any taxes or amounts in lieu thereof paid or payable by SPAN in respect of the foregoing, exclusive however of personal property taxes assessed on the System and taxes based on SPAN'S net income.

THIS AGREEMENT INCLUDES THE PROVISIONS ON THE REVERSE SIDE AND FOLLOWING PAGES.

This Agreement is subject to written acceptance by an authorized officer of SPAN International, Inc., at Scottsdale, Arizona.

Accepted by:	**User:**
SPAN International, Inc. 7330 Shoeman Lane Scottsdale, Arizona 85251	________ ________ ________
By: ________	By: ________
Title: ________	Title: ________
Date: ________	Date: ________

APPENDIX A

TERMS AND CONDITIONS

TERM OF AGREEMENT

This Agreement shall become effective on the date it is accepted by SPAN and shall remain in effect until cancelled or terminated as herein provided. User's obligation to pay the Basic Charges, and all other charges provided for herein which shall have accrued, shall survive any termination of this Agreement.

DELIVERY

SPAN will confirm a delivery date no later than three (3) working days after receipt of the Mobilization Fee and will provide the System at the Airport of Delivery on the delivery date confirmed by SPAN. SPAN shall not be liable for delays in delivery (1) due to causes beyond its reasonable control, or (2) to Acts of God, acts of the User, acts or restrictions of civil or military authority, priorities, fires, strikes, labor disputes, floods, epidemics, war, riots, or civil commotion, shortages of labor or materials, delay in transportation, or other similar or dissimilar causes, or (3) unavailability of information or material to be furnished by the User.

Span's Obligations

VEHICLE

SPAN will provide a suitable land vehicle for use with the System if the User has specified the System is to be operated in a land vehicle.

INSTALLATION OF SYSTEM IN VEHICLE OR HELICOPTER

SPAN shall be responsible for installation of the System in the vehicle or User-provided helicopter. SPAN shall provide required installation materials, tools, and accessories necessary for installation of the System in the vehicle or helicopter.

PERSONNEL

SPAN will provide reasonable technical assistance in planning for inertial surveying and will provide the services of one Project Manager; and one or more Field Engineers and/or Technicians, who will accompany the System, operate the System for the User as well as provide field maintenance for the System and oversee the System performance. SPAN'S Project Manager will also be SPAN'S Contract Representative and be responsible for providing the end product survey data from the System to the User. Employees of SPAN shall be under the exclusive control and management of SPAN and shall not be considered employees or agents of User.

MAINTENANCE

During the term of this Agreement, SPAN, at its expense, will cause to be made all necessary adjustments, repairs, and replacement of parts required to keep the System in good working order. If maintenance on the System reduces the available work hours below an average of 7 hours per day for the Base Term, then in that event *SPAN'S sole and exclusive liability to User shall be to extend the* Base Term 1 day for each 7 hours of such reduced availability at no additional cost to User. Such extension shall in no way reduce User's obligation to pay the Basic Charge or other charges for the Base Term or pay Basic Charges or other charges for subsequent periods.

SYSTEM OPERATION AND SUPPLIES

The System shall be operated in accordance with SPAN'S operational procedures and this Agreement. All supplies used in the System will be supplied by SPAN. SPAN will, within fourteen (14) days after the conclusion of the Base Term, provide User with final System traverse results in hard-copy and, if requested, magnetic tape.

TRANSPORTATION

SPAN shall be responsible for transportation of the System and SPAN'S personnel to the Airport of Delivery to commence the Base Term. Upon completion of the Base Term, SPAN shall be responsible for transportation of the System and SPAN'S personnel from the Airport of Delivery to SPAN.

INSURANCE

SPAN shall maintain a standard form All-Risk Casualty Insurance Policy covering the System during the term of this Agreement and while the System is in transit.

User's Obligations

PROJECT SUPPORT AND ACCESS TO SYSTEM

User, at its expense, shall provide adequate office and working space, storage for spare parts, heat, light, ventilation, and 120 volt electrical power required for installation, operation, maintenance, and support of the System. Such facilities shall be within a reasonable distance of the alignment point and where the System is to be serviced. Additionally, all control, survey materials, fuel, jobsite(s) transportation, parking, security, permits, etc., shall be provided by User at its expense. User shall provide satisfactory lodging (2 rooms) and provisions for SPAN'S employees at its expense during the Base Term or any extension thereof. If in the opinion of SPAN'S Project Manager, such lodging and provisions are not satisfactory, he may give written notice to the User's Field Representative and SPAN'S Project Manager may then secure temporary support facilities and SPAN will charge User $100 per day for each onsite SPAN employee until satisfactory lodging and provisions are provided by User. Employees of SPAN shall have access to the System at all times.

PERSONNEL

The User will provide a qualified surveyor to be in professional charge of the survey and be the User's Project Manager, and such additional personnel needed for the project including a driver, if requested, for the SPAN-provided land vehicle. User's employees and personnel shall be under the exclusive control and management of the User and shall not be considered employees or agents of SPAN.

HELICOPTER

If the User elects to have the System operate from a helicopter, the User agrees to provide a suitable helicopter, pilot(s), supplies, and maintenance acceptable to SPAN.

INSURANCE AND INDEMNIFICATION

If User elects to provide the vehicle or helicopter, User shall maintain liability insurance coverage acceptable to SPAN for injuries to persons and property in connection with the equipment with coverages of not less than One Million Dollars ($1,000,000) per person, Five Million Dollars ($5,000,000) per accident, and One Million Dollars ($1,000,000) property damage. Such insurance shall name SPAN, the Manufacturer, and the Owner as additional insureds, and User shall upon request, deliver a certificate of such insurance to SPAN which requires ten (10) days' prior notice to SPAN of cancellation or modification. User agrees to hold harmless and indemnify, as a surety, SPAN, the Manufacturer, and the Owner against any and all claims, liabilities, or damages including claims, liabilities or charges by User for personal injuries, property damage, loss of business, loss of profits, loss of anticipated profits, other economic loss, expense, or otherwise.

TITLE

The System is, and will remain personal property. User will defend, at its expense, the title of Owner and SPAN against all persons claiming an interest in the System through or against the User, and the User will not create or permit any lien or encumbrance upon the System. User shall not assign its rights and interests under this Agreement, nor shall it sublet the System, without prior written approval of SPAN.

PUBLICATION RELEASE

User agrees to allow SPAN to identify User's company name and project in SPAN publications as a User of the System covered by this Agreement. If material is written for placement in public media, the text thereof will be submitted to User in advance for his review and approval.

General Terms

USE TIME

Use time is that time during which the System is being operated in inertial surveying operations and includes calibration and alignment of the System before surveying operations begin. Use time shall commence at the beginning of alignment and continue until the last terminal update. Use time shall not be accumulated during the time required for System maintenance.

DEFAULT

In the event that any one of the following events shall occur: The User fails to make any payment at the time and in the manner herein contracted to be paid and continues in default more than five (5) days after written notification by SPAN; or, the User shall, for more than five (5) days after SPAN shall have demanded in writing the performance thereof, fail or refuse to comply with any other of the convenants, agreement, terms, or provisions of this Agreement on its part to be kept and performed; or, a petition for reorganization or debt adjustments is filed under the Bankruptcy Act, or under any amendment or revision thereof, affecting the obligations of the User under this Agreement; or, any proceedings are commenced by or against the User for any relief under any bankruptcy, insolvency laws, laws relating to the relief of debtors, readjustments, compositions or extensions or otherwise; or, there shall occur any voluntary or involuntary assignment or transfer of the User's rights or interest in this Agreement, whether under the bankruptcy laws or by the appointment of a receiver or trustee, or by any judicial or administrative decree or process or otherwise; or, the User shall make or suffer to be made any unauthorized use or sublease of the System; or, the System be pledged or held for any debt or obligation owing by User, or to be in any manner encumbered, or shall part with the possession of the System, SPAN may declare the User to be in default.

REMEDIES UPON DEFAULT

In the event of default by the User: SPAN shall have the right to take immediate possession of the System, and the User hereby waives any action for trespass or damages resulting from a peaceable repossession of the System; and, this Agreement, which shall terminate upon the declaration of default, shall in no way be treated as an asset of the User; and, the User shall remain and be liable for the payment of the unpaid balance of the remaining Basic Charges and all unpaid additional charges for the Base Term, and all such unpaid obligations or charges shall become immediately due and payable as of the date of said declaration. All remedies conferred upon SPAN under this Agreement shall be deemed to be cumulative and no one exclusive of the other, or any other remedy conferred in any manner in equity. SPAN shall be entitled to receive from User all costs and attorneys' fees incurred in enforcing its rights hereunder. Additionally, SPAN shall have all rights and remedies afforded by the laws of the State of Arizona, U.S.A., or any jurisdiction in which the System may be located.

LIMITATION OF LIABILITY

IN NO EVENT SHALL SPAN, THE OWNER, OR MANUFACTURER BE LIABLE TO USER OR ANYONE ELSE FOR ANY INDIRECT, SPECIAL, CONSEQUENTIAL, OR OTHER DAMAGES, INCLUDING WITHOUT LIMITING THE GENERALITY OF THE FOREGOING, DAMAGES FOR OR DUE TO: NEGLIGENCE, PERSONAL INJURIES, PROPERTY DAMAGE, LOSS OF BUSINESS, LOSS OF PROFITS, LOSS OF ANTICIPATED PROFITS, OTHER ECONOMIC LOSS, CUSTOMERS OF USER, EMPLOYEES OF USER, OR ANY DAMAGES ARISING OUT OF, CONNECTED WITH, OR RESULTING FROM THE SYSTEM, ITS MANUFACTURE, SELECTION, DELIVERY, POSSESSION, USE, OPERATION, NON-PERFORMANCE, DEFECTIVE PERFORMANCE, OR OPERATION. NO ACTION, REGARDLESS OF THE FORM, ARISING OUT OF THE TRANSACTIONS UNDER THIS AGREEMENT MAY BE BROUGHT BY THE USER MORE THAN SIX (6) MONTHS AFTER THE CAUSE OF ACTION OCCURRED.

GENERAL

This Agreement is not a sale, but a form of rental agreement. The User agrees that this Agreement constitutes the entire understanding between the parties with respect to the subject matter hereof and that this Agreement supersedes all proposals, oral or written, all previous negotiations, and all other communications between the parties with respect to the subject matter hereof, and may not be modified other than by a written instrument signed by all parties affected by such modification. The terms and conditions of any purchase order or other instrument issued by User in connection with this Agreement which are in addition to or inconsistent with the terms and conditions of this Agreement shall not be binding on SPAN or its assignees and shall not apply to this Agreement. The paragraph headings used herein are inserted for convenience only and shall not be constued to limit or modify the scope of any provisions of this Agreement. This Agreement (and any amendments hereto) shall be governed by the laws of the State of Arizona. This Agreement shall be binding upon the User, its successors and assigns, and shall be binding upon and inure to the benefit of SPAN, its successors and assigns, from the date of execution hereof. Changes in or attachments to the System by the User are absolutely prohibited. All of the covenants and agreements contained herein are severable and in the event that any of them shall be held to be invalid by any competent court, this Agreement shall be interpreted as if such invalid covenant or agreement were not contained herein. Time is of the essence in this Agreement, and of each and all of its provisions. SPAN may impose a late charge of one and one-half percent (1-1/2%) or the highest legal rate permitted by law, whichever is lower, per month on any charges not paid when they become due. Any notice from SPAN to User shall be effective upon Telex transmission or effective twenty-four (24) hours after deposit in United States mail, postage prepaid, to User's address shown herein or subsequently given to SPAN in writing. Waiver of any provision hereof by SPAN must be in writing and shall not affect any subsequent condition, breach, or default.

Appendix B

Guidelines for Accurate Inertial Surveys*

The following items are listed in general order of importance for obtaining the best accuracy using the ISS. In field conditions any of these guidelines may be violated in a particular survey. As the survey deviates from these guidelines, accuracy will be somewhat reduced, with the magnitude dependent upon the severity of the deviation and the number of times or items deviated from.

1. Control - Positional accuracy of any survey is limited to that of the control. The survey should be based on the highest order control available, but also should be tied (but not adjusted) to all reasonably available control in the immediate vicinity of the survey. This will provide maximum correlation between the new survey and the basic control in the area. Positive identification and proper coordinates of all control used must be obtained.

2. Calibration - The system should be calibrated accurately to local survey control of the highest order available. The system should be recalibrated if raw closures (before smoothing) fall to 1:10,000 between verified control. Gyro drift should be checked regularly and recalibrated if it exceeds 6 seconds per hour.

3. Linear traverses - The results are obtained if the rate of change of latitude and longitude are linear with respect to time. This suggests, as nearly as practical, minimum meander between terminal control points and a uniform rate of travel. As a rule of thumb, the survey should stay within a diamond, the apexes of which are the two control points and no point of which shall be offset from the centerline more than 1/3 of the distance from the nearest control point. Slightly better results are obtained if the offset is kept to 1/12. Zero velocity updates should be performed uniformly with the same distance and time (but most importantly time) between them. There should be no delays in the survey (see Item 4) nor any doubling back (to pick up a missed point, for instance) if at all possible.

4. Minimum travel time - The traverses should be carefully planned and reconnoitered so that the survey can be run with a minimum amount of travel time between terminal control (updates); with no delays for closing control or point searches, refueling, operational restrictions, or personal activities (lunch, break, etc.) that would make travel time nonlinear. Assuming that operational precision remains constant, the maximum absolute error is directly proportional to the time and distance between control points. Therefore, if time and distance between control points can be reduced, the absolute error will normally also be reduced.

5. Double runs - Control traverses should be run both forward and reverse during the same alignment and the two values averaged. The

*From Wickham (7)

remaining coordinate error is only approximately half that of a single traverse because of the systematic nature of system errors. Two runs in the same direction only slightly (20%) improve the results.

6. ZUPTS - Zero velocity updates should be performed at uniform 3 to 5 minute intervals. Longer intervals generally reduce the accuracy at an increasing rate with respect to time. Irregular intervals cause significant reduction of accuracy. In a helicopter operation, landed ZUPTS are preferred to hovered ZUPTS whenever possible. When hovered ZUPTS must be used, it is best to follow them by landed ZUPTS as soon as practical. Hovers should be performed as low as possible, and avoided during gusty wind conditions. A stabilized or ground hover improves results.

7. Alignment - The vehicle should not be subjected to any movement during alignment. Parking on mud, snow or other yielding surfaces should be avoided or if impossible to avoid, the vehicle should be parked in its final position several hours in advance of beginning the alignment. Wind effects should be minimized. Park away from heavy traffic with the vehicle oriented parallel to the wind or protected. Helicopter blades should be tied down at all blade tips.

8. Helicopter pilots - The helicopter pilot must be well-trained to obtain maximum efficiency and accuracy. He must be able to place the helicopter accurately and quickly at the desired location under all conditions to be expected. During hover operations, the minimum computer tolerance for repeatability that the pilot's skill and the conditions will permit should be used.

9. Pre-Survey - The system should be warmed up for 20-30 minutes prior to starting on alignment. Before starting the day's survey operations, one or two short traverses should be run between two valid control points. These may be as short as a mile or two in length and 15 minutes in time and serve the purpose of providing data on which the Kalman filter can base future adjustment and corrections to the system.

10. Stable ZUPTS - The vehicle should be stable during zero velocity updates. This is particularly true of the first 10 seconds of the ZUPT period. Do not get in or out of the vehicle during this period. Helicopters with floats, articulated landing struts or excessive vibration are usually unsatisfactory.

11. Minimum travel distance - The distance between points should be the shortest available and the most direct route should be used.

12. Gravity anomalies - Large changes in gravity between ZUPTS should be avoided if possible. The system gives an automatic warning if a change of more than 16 milligals occurs between ZUPTS and the ZUPT period is extended automatically to compensate. If large gravity gradient changes are anticipated, zero velocity updates should be at shorter intervals with 1-1/2 to 2 minutes found to handle all gradients experienced to date.

13. Smooth travel - All travel should be accomplished in as smooth a manner as practical, avoiding chuckholes, wash boards, rough sudden stops, unnecessary direction changes and any other extreme accelerations.

14. Time distance limit - Traverses should not exceed 600 mile hours (distance travelled times time travelled) without special procedures because of IPE and IPN overflow.

15. Adjacent points - Points less than 500 feet apart should normally be set with an offset device for best relative accuracy. Closely spaced points (1 mile or less) should be included in the same traverse, or adjacent points in different traverses should be tied together with cross flights. Whenever practical, surveys should be adjusted using a least squares grid adjustment.

Following the guidelines presented above produced accuracies in excess of 1:70,000 $\pm$ 10cm (1σ) relative to the nearest control. Accuracy of this level is necessary only for first order control or a few other projects. For most projects, accuracy of 1:10,000 + 10cm (1σ) is more than adequate and has consistently been obtained with a well-calibrated ISS system in real time without smoothing. Therefore, adherence to the restrictions listed above and in the published literature (such as straight line traverses) is not absolutely necessary for most projects other than high order control.

Appendix C

Positions of Fixed Aids to Navigation

As Determined by the Inertial Surveying System

	LATITUDE	LONGITUDE	ELEVATION (Meters)
Tampa Bay Cut C Range, forward light	27° 42' 11.379"N	82° 32' 15.372"W	8.29
Tampa Bay Cut F South Range, forward light	27° 44' 31.959"N	82° 31' 22.313"W	7.50
Tampa Bay Cut F South Range, rear light	27° 43' 57.237"N	82° 31' 22.064"W	17.30
Tampa Bay Cut G Range, forward light	27° 47' 33.756"N	82° 35' 14.367"W	3.41
Tampa Bay Cut J Range, forward light	27° 45' 53.189"N	82° 34' 21.574"W	6.20
Tampa Bay Cut J Range, rear light	27° 45' 01.899"N	82° 34' 20.315"W	18.21
Tampa Bay Cut J2 Range, forward light	27° 50' 18.314"N	82° 34' 04.178"W	5.58
Tampa Bay Cut J2 Range, rear light	27° 50' 43.174"N	82° 33' 59.192"W	12.95
West Bend Stack (striped)	27° 47' 39.686"N	82° 24' 14.539"W	

Appendix D

Field Preparation for an Inertial Survey*

The user's surveyor must make the following preparations prior to the execution of an inertial survey.

1. Research all the available control stations in the immediate area of the positions to be surveyed.

2. Identify all stations and assess their potential use as a helicopter landing site. Power lines, buildings, walls, etc., directly inhibit safe flight. Air traffic routes must be given consideration when operating in the vicinity of an airport.

3. At many stations it will be necessary to obtain permission to land. Contact the owners, public or private, prior to using the station. Permission will usually be granted once the helicopter operation is explained.

4. Clear all debris from the landing area and prepare the site so the helicopter may rest firmly on the ground.

5. For those stations without clear access for landing or takeoff, establish an offset to a more suitable point. Precomputation of the points' geographic coordinates is always desirable and sometimes absolutely necessary when used as an endpoint.

6. Target or flag all landing sites to be visible from the air.

7. Prepare a sketch of each site and identify any prominent landmarks for the pilot.

8. List the stations and their approximate coordinates in the order the traverse will be flown. This list greatly simplifies the task of the pilot and ISS operator.

9. Perform an aerial reconnaissance of the area, preferably with the pilot, a short time before conducting the survey. This is to insure that all flagging is intact while also acquainting the pilot with the flight routine. Avoiding confusion at the time of the survey is essential for efficient use of the system rental time.

*From Penney (2)